

# Bioplastics offer carbon-cutting advantages but are no panacea

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For at least 20 years, a few companies looking to enhance their green credentials have been making products out of bioplastics—polymers derived from plants, wood chips, food waste, and other renewable materials instead of oil or natural gas. In principle, bioplastics can be a welcome alternative to the fossil fuel-based plastics that represent a growing environmental scourge across much of the globe. And with advances occurring at a rapid pace, bioplastics may yet fulfill that promise.

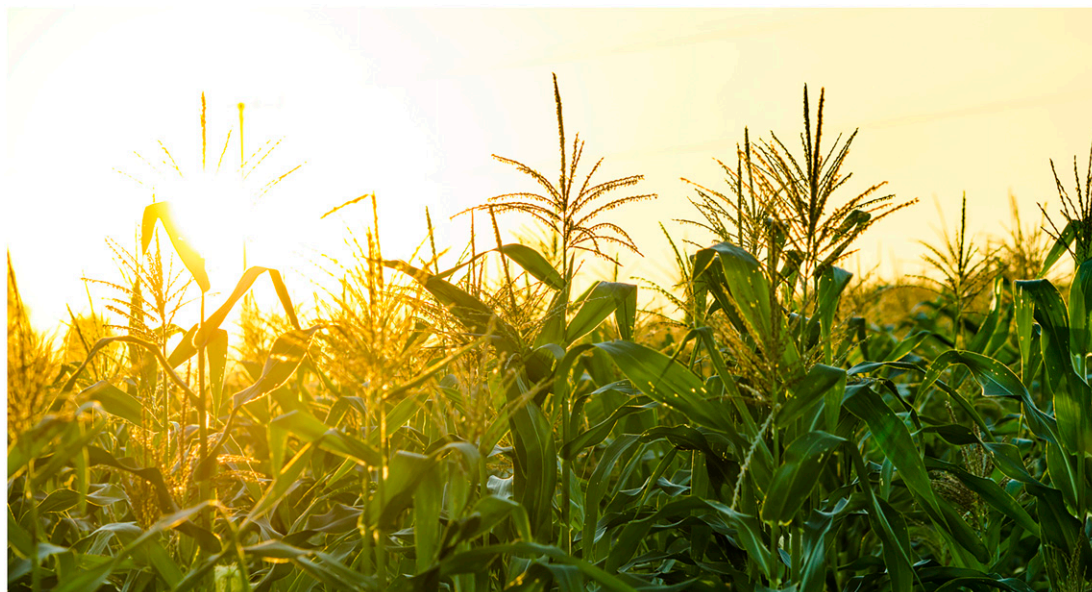
For now, however, there are serious questions about how sustainable and climate-friendly bioplastics actually are, especially once you account for all the fuel, water, and fertilizer required to produce them. Likewise, there's plenty of confusion over bioplastics' biodegradability—whether this assortment of materials will quickly break down and be consumed by microorganisms in the environment instead of piling on beaches and in landfills. By better understanding the various tradeoffs presented by different bioplastics, researchers, companies, and policymakers might be

able to better determine which options, if any, are viable replacements for conventional plastics over the long run.

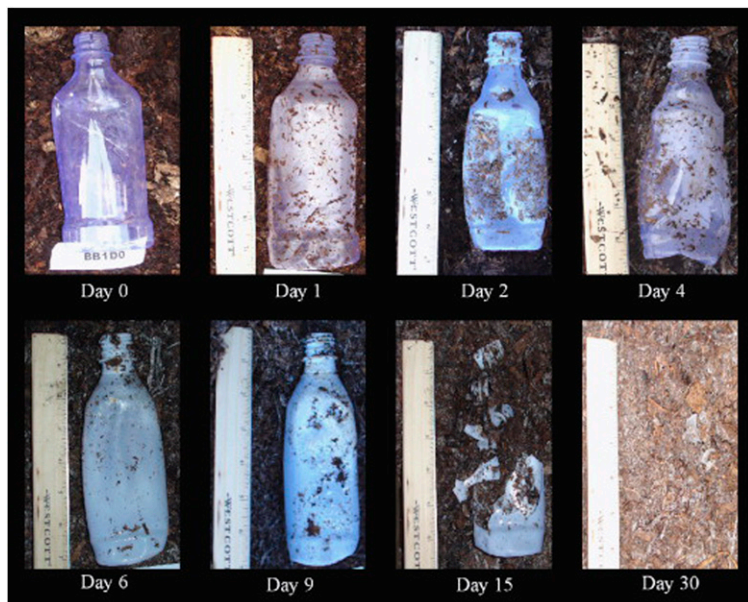
## Historic Attempts

"Bio-based" plastics made from organic material are hardly a new idea. Humans have been using latex-rich plant sap to make balls and other elastic items for thousands of years. In the 1850s, chemists developed the first commercial synthetic polymer by combining nitrocellulose derived from wood pulp with camphor extracted from laurel trees. Dubbed "celluloid," the material quickly became a popular replacement for ivory knife handles, chess pieces, and the like and was used in applications such as ping pong balls and movie film well into the 20th century. Galalith, a milk-based plastic invented in the 1890s, is another ivory-like material that's still used for buttons.

But bio-based polymers like these largely fell by the wayside in the 20th century, when the burgeoning petroleum industry made it much cheaper and easier for plastics manufacturers to use oil- and gas-based



Corn is among the feedstocks used to make bioplastics, even though it's not a particularly green crop owing to the amount of fertilizer and water it requires. Image credit: Shutterstock/TB studio.



With the right composting conditions, PLA bottles readily biodegrade after about 30 days. Image credit: Reprinted with permission from ref. 3.

feedstocks. Interest in bioplastics didn't begin to revive until 2000 or so, as it became harder and harder to ignore how all those long-lived "petroplastics" were fouling the oceans and choking wildlife, not to mention contributing to climate change.

One of the pioneers in this revival has been the Minnesota-based firm NatureWorks, which in 2002 opened a factory in Blair, NE, that turns cornstarch into about 150,000 tons per year of polylactic acid (PLA)—a polymerized form of the same lactic acid that makes muscles sore and sauerkraut sour. Things were "rather quiet" for the first 15 years after the plant opened, says NatureWorks' sustainability manager, Erwin Vink. NatureWorks had the PLA market pretty much to itself (and is still the world's largest producer). But PLA has proved to be an attractive alternative to petroplastics for three-dimensional (3D) printer filaments, coffee capsules, plastic cups and cutlery, N95 medical masks, and an increasingly wide range of other items. And unlike their oil-based counterparts, PLA items are at least somewhat biodegradable: They will break down into a rich organic loam in industrial composting facilities.

As a result, says Vink, demand for PLA has skyrocketed. NatureWorks is expanding its capacity in Blair, and other companies have begun rushing into the market. The Dutch firm Total Corbion, for example, has opened a 75,000-ton-per-year factory in Thailand to make PLA from sugar cane and is planning to build a 100,000-ton-per-year plant in France. China is expanding its PLA capacity as well. And even with the uptick in production, NatureWorks and its competitors can't meet the global demand. It's a similar case for bio-based polymers such as the polyhydroxyalkanoates (PHAs): a large, versatile family of plastics made via the bacterial fermentation of sugars and fats.

Global production of all types of bio-based polymers is estimated to be about 3.8 million metric tons per year and is expected to grow by 3% annually at least until 2024. Of course, that tonnage is only about 1% of the annual production of petroplastics, which are growing at the same rate. And until the bioplastics industry can answer a variety of open questions about their viability, it's not at all clear how far that fraction can expand.

### Plastic Perils

One obvious sticking point is cost: Bioplastics are typically more expensive than their petroplastic counterparts. This is partly because the latter have a hundred-year head start: Bioplastics tend to be made in smaller plants that don't enjoy Big Oil's economies of scale. "There's just so much efficiency built into a hugely scaled system like the petroleum industry," says Troy Hottle, a sustainability engineer with the consulting firm Eastern Research Group in North Carolina's Research Triangle.

Added to that, says Constance Ißbrücker, head of environmental affairs for the Berlin, Germany-based industry association European Bioplastics, oil and gas prices are comparatively low at the moment. "I always like to say that bioplastics are not expensive," she says, "conventional plastics are too cheap."

On the other hand, as Vink points out, price isn't everything. When oil prices plummeted during the 2008–2009 financial crisis, he says, "we thought our PLA customers would flee. But they didn't." And they likewise stayed loyal when oil prices cratered during the pandemic shutdown that began in April 2020.

"For certain applications there are no good alternatives," Vink explains. For example, PLA's combination of high finish quality, low shrinkage, durability, and other properties have made it the preferred choice for 3D printer filaments. PLA film also makes a superior liner for the insulation in a refrigerator, reducing the appliance's long-term energy use by as much as 12.5% over the standard polystyrene liner. And PLA can be incorporated into a medical face mask that provides excellent protection against coronavirus disease 2019 (COVID-19). "You can make it into very fine fibers to filter very small particles," says Vink.

But then there's the issue of biodegradability. A lot of confusion arises from that prefix *bio*, says Daniel Posen, an engineer who studies the economics and sustainability of plant-derived chemicals at the University of Toronto in Canada. "There is a conflation sometimes between biodegradable and bio-based," says Posen. There are oil-based plastics that are biodegradable because they have been engineered that way—and that are sometimes called "bioplastics" for that very reason. And there are plant-derived bioplastics that are not biodegradable.

A prime example of the latter is Coca-Cola's PlantBottle, which has been replacing more and more of the company's petroplastic water bottles and soft-drink bottles since its introduction in 2009. The good news is that the polymer in the PlantBottle comes from renewable feedstocks such as wood chips





Microscopic green algae and photosynthetic cyanobacteria, also known as blue-green algae, can be used to efficiently create bio-based products with minimal fossil fuel inputs. Green algae (shown here) generate lipids to create biofuels; cyanobacteria efficiently produce sugars that can easily be turned into polymers such as PLA. Image credit: Science Source/Pascal Goetgheluck.

or sugar cane instead of oil or natural gas; Coca-Cola estimates that its use has already achieved carbon savings equivalent to taking 1 million vehicles off the road. And because that polymer is polyethylene terephthalate (PET), which is chemically identical to the PET used in the original bottles, PlantBottles can be recycled in exactly the same way. But that last point is also the bad news: Bio-based PET is just as resistant as conventional PET to breakdown out in the open; the PlantBottle isn't remotely biodegradable.

There are polymers such as PHA that are both bio-based *and* biodegradable. But biodegradability isn't always a virtue. When PHA items are covered over in a landfill, as plastics often are, their breakdown releases methane that can migrate to the surface where it becomes an extremely potent greenhouse gas. Based on his life-cycle analyses (1), says Posen, "my conclusion is that PHA might actually be worse for the climate than oil-based plastics."

An important intermediate case is PLA, which is produced at more than 10 times the volume of PHAs. A PLA item will stay whole if it's sealed inside a landfill, so that it won't be a big source of methane. Unfortunately, it will also tend to stay whole if you toss it into the open environment. The action of sunlight, water, and microbes will break it down into environmentally benign compounds within a hundred years or so, which is better than the multi-century timescales of conventional plastics such as PET. But the decay still isn't fast enough to be called PLA "biodegradable." PLA will break down in a composting bin—just not in most home composting units, which is where things like PLA-containing tea bags tend to wind up. The

polymer breakdown doesn't begin until the temperatures are above 60 °C, which is more typical of large industrial composting units.

PLA manufacturers such as NatureWorks have accordingly put a high priority on making this composting process faster, easier, and better suited to home units. One approach is to insert non-lactic-acid monomers into the polymer chain to assist with the breakdown—but without compromising the properties that make plastics valuable in the first place, such as their stiffness and transparency. "We are not there yet," says Vink, "but we're still looking."

### Careful Assessments

These challenges feed into a larger puzzle: calculating bioplastics' overall impact on the environment. A total life-cycle analysis—one that includes the fuel required for tractors and harvesting machines, the effects of clearing land, and so on—suggests that bioplastics' effect on greenhouse gas production is not clear-cut. "Anytime you're dealing with agriculture," says Posen, "you have to worry about land use, runoff, fertilizer, deforestation, and extra energy use." That last item might include the fuel used to dry the crops before processing. From this life-cycle perspective, he says, "sugarcane is a relatively green crop. But corn, not so much." Corn needs a lot of fertilizer, Posen notes, not to mention water, which is often scarce.

On the other hand, it's notoriously hard to make any kind of general statement about an industry using life-cycle analysis; the results can vary wildly depending on the precise details of when, where, and how a given product is produced. Posen points to the

peer-reviewed life-cycle studies that Vink and his colleagues have carried out on the specifics of NatureWork's PLA production (2). Because the company chose to locate its plant in Nebraska/Iowa corn country, there is little additional climate impact from factors like transportation from farm to factory or changes in land use. When combined with the fact that corn plants pull carbon dioxide out of the atmosphere, this means that the overall greenhouse emissions from NatureWork's PLA are about 60–80% lower than from the equivalent oil-based plastics.

But that doesn't really address a related sustainability issue: Bioplastics such as PLA are being made from food that might otherwise feed people or livestock. This isn't a big problem now, because the bioplastics industry currently uses the output from just 0.015% of the world's arable land. But it could become a real constraint if and when bioplastic production ramps up in a major way. "If you're trying to get enough sugar from corn to fulfill all our plastic needs," says Danny Ducat, a biochemist at Michigan State University in East Lansing, "you're looking at covering 20 to 25 US states with just cornfields."

One obvious alternative is to use nonedible, cellulose-rich biomass such as corn stalks, wood chips, and switchgrass—a collection of sources that has also attracted a great deal of interest in the biofuels industry, which seeks to turn the stuff into ethanol. But the grinding, chemical pretreatments, and enzymes required to handle this kind of feedstock are much more expensive and complex than the relatively simple fermentation of cornstarch, explains Vink. So it's still not cost-effective for companies like his. "Biofuels are heavily subsidized," he says. "We are not."

### Algae Alternative

Another approach would be to cut out conventional agriculture entirely—a move that would not only eliminate bioplastics' competition with food but would also allow for the feedstock production in contaminated "brownfields" and other spaces not suitable for crops. The idea is to streamline the current two-step process, in which higher plants such as corn

first turn sunlight, water, and carbon dioxide into complex molecules, and a standard microbial fermentation process then turns the resulting biomass into monomers such as lactic acid and ethanol. Instead, certain photosynthetic microbes would be coaxed into synthesizing the desired molecules in one go.

Various species of microscopic green algae have been extensively studied for this purpose, as have photosynthetic cyanobacteria—a family of prokaryotes sometimes still referred to by their old name, "blue-green algae." These two groups are nicely complementary, says Ducat, who works on cyanobacteria at Michigan State. Algae naturally accumulate lipids, which can be used in things like biodiesel, he explains, whereas cyanobacteria efficiently produce sugars, which can easily be turned into polymers such as PLA. And the groups also share a huge advantage over macroscopic crops: "They have a much more efficient photosynthetic process," says Ducat. So in principle, he says "you could realize the same amount of bio-productivity on one tenth or even one twentieth the land."

The trick, says Ducat, is to achieve that productivity in practice—at an acceptable price. "Right now," he says, "you can dig a trench, fill it with water, and grow your algae and cyanobacteria the cheap way." But then you end up with ponds as big as any cornfield—not to mention a huge risk of having your micro-crops decimated by contaminants and microscopic pests.

Or you can go the high-tech route, says Ducat, and grow your cyanobacteria and algae in glass or plastic bioreactors. That gets the bio-efficiency way up and protects the crop from micro-predators. "But then the cost of growing them becomes much higher," he says.

Still, says Ducat, he sees plenty of opportunities to reduce the cost of these bioreactors through clever design and the use of cheaper materials. With enough innovation, he says, "your tiny bacteria and algae are still going to be economically competitive." Whether that will be enough to make bioplastics a viable, widely available petroplastics alternative in the years to come remains to be seen.

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- 1 I. D. Posen, P. Jaramillo, W. M. Griffin, Uncertainty in the life cycle greenhouse gas emissions from U.S. production of three biobased polymer families. *Environ. Sci. Technol.* **50**, 2846–2858 (2016).
  - 2 E. T. H. Vink, S. Davies, Life cycle inventory and impact assessment data for 2014 Ingeo™ polylactide production. *Ind. Biotechnol.* (New Rochelle N.Y.) **11**, 167–180 (2015).
  - 3 G. Kale et al., Compostability of bioplastic packaging materials: an overview. *Macromol. Biosci.* **7**, 255–277 (2007).